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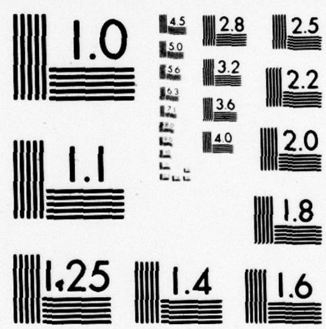

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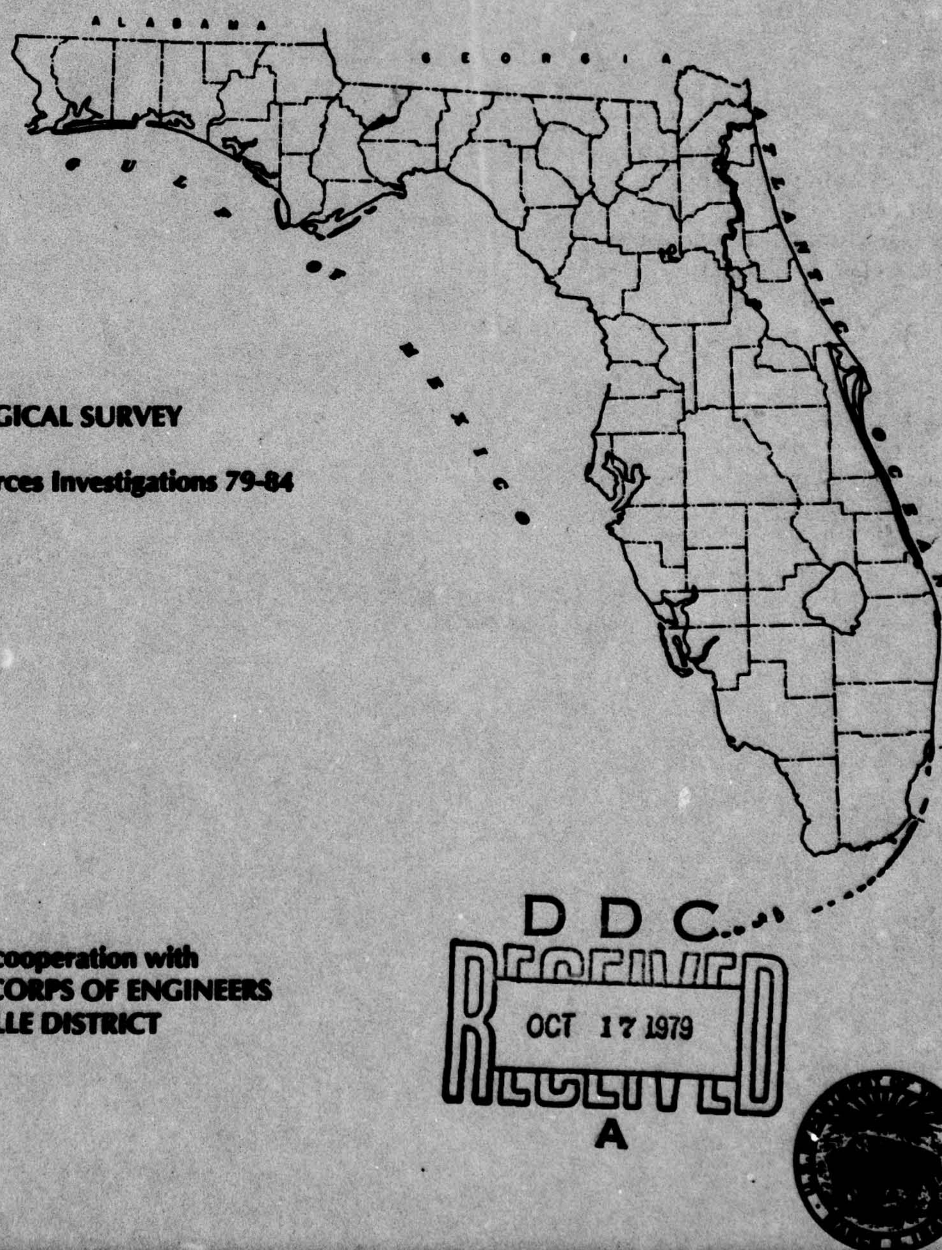

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 79-84

Prepared in cooperation with
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16. Abstracts Hydrologic investigations of the Floridan aquifer in Duval County, Florida, have shown that an appropriate simplified model of the aquifer system consists of a series of sub aquifers separated by semipermeable beds. Data from more than 20 aquifer tests in the county were reanalyzed by the Hantush modified method, which takes into account leakance from all confining units. Transmissivity values range from 2.0×10^4 to 2.4×10^5 feet^2/day. Leakance was estimated to be 2.5×10^{-6} and 3.3×10^{-5} per day for the upper and lower confining units, respectively. Families of steady-state, distance-drawdown curves were constructed for three representative transmissivity values based on hypothetical withdrawals from a point source ranging from 5 to 50 million gallons per day. Transient effects were not considered because the system reaches steady-state conditions within the time ranges considered. Drawdown at any point can be estimated by summing the effects of any hypothetical configuration of pumping centers. The accuracy of the parameters was checked by comparing calculated drawdowns in selected observation wells to measured water-level declines.

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DUE TO INCREASED WITHDRAWALS, DUVAL COUNTY, FLORIDA

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JACKSONVILLE DISTRICT

1979

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

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For use of those readers who may prefer to use metric (SI) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound units	By	To obtain metric (SI) units
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
cubic foot (ft^3)	.0283	cubic meter (m^3)
foot squared per day (ft^2/d)	.0929	meter squared per day (m^2/d)
million gallon (Mgal)	3,785	cubic meter (m^3)
gallon per minute (gal/min)	.06309	liter per second (L/s)
million gallon per day (Mgal/d)	.04381	cubic meter per second (m^3/s)

ESTIMATED DRAWDOWNS IN THE FLORIDAN AQUIFER DUE TO INCREASED WITHDRAWALS, DUVAL COUNTY, FLORIDA

By B. J. Franks and G.G. Phelps

ABSTRACT

A simplified model of the Floridan aquifer system underlying Duval County consists of two highly permeable water-bearing zones separated by a semiconfining zone of relatively low permeability, all of which are confined above and below by much less permeable strata. At present (1979) only the upper permeable zone is tapped by production wells.

20,000 TO 200,000

Data from more than 20 aquifer tests were analyzed. From these tests, transmissivity of the major pumping zone was determined to range from 2.0×10^4 to 2.0×10^5 feet squared per day. Leakage was estimated from laboratory analyses and field extensometer tests to be 2.5×10^{-6} and 4.0×10^{-5} per day for the upper and lower confining units, respectively.

200,000, 80,000, and 20,000

Families of steady-state distance-drawdown curves for the upper permeable zone were constructed based on estimated withdrawals from a point source of 3, 5, 20, and 50 million gallons per day and aquifers transmissivity values of 2×10^5, 8×10^4, and 2×10^4 feet squared per day. Transient effects were not considered because the system reaches steady-state within the time range considered.

Decreases in artesian pressure in the upper permeable zone of the aquifers induce upward leakage of water from the lower permeable zone resulting in reduced pressure in this zone. Thus, saline water from deeper strata can move upward, apparently along fractures and faults into the lower permeable zone.

INTRODUCTION

The Floridan aquifer is the major source of potable water in Duval County. In 1975, approximately 150 Mgal/d were withdrawn from the upper permeable zone of the aquifer. Continuing population growth and industrial development will place increasing demands on the aquifer.

Hydrographs of wells in Duval County show a decline in artesian water levels of about 0.5 foot/year, probably because of the increased withdrawals. Declines in water levels are accompanied by increased pumping costs.

A more serious result of declining water levels in northeast Florida, however, is the deterioration of water quality. Increases in chloride and dissolved solids concentrations in the water from at least two Jacksonville city production wells and several observation wells in eastern Duval County have accompanied declining water levels.

Hydrologic investigations by the U.S. Geological Survey indicate that upward leakage of saline water through the lower semiconfining zone may be a major threat to water quality in the Jacksonville area sooner than, for example, lateral intrusion from seawater in the major pumping zone. Decreases in artesian pressure in the upper freshwater zone of the aquifer induce upward leakage of water from the lower permeable zone, resulting in reduced pressure in the lower zone. Saline water can then enter the lower permeable zone by upward movement from the underlying Cedar Keys Limestone through vertical conduits along faults or solution channels, or by lateral seawater intrusion.

Purpose and Scope

In order to plan for future water usage in Duval County, it is necessary to understand the Floridan aquifer system and its response to stress. The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, Jacksonville District, is evaluating hydrologic properties of the aquifer system in Duval County. Ongoing studies confirm that an appropriate simplified model of the Floridan aquifer system in Duval County consists of two highly permeable water-bearing zones separated by a semiconfining zone of relatively low permeability, all of which are confined above and below by much less permeable strata. An analytical method for evaluating layered aquifer systems described and modified by Hantush (1956, 1960) was chosen as the primary tool for evaluating the effect of increased withdrawals from the Floridan aquifer.

The report provides estimates of drawdown in the upper (producing) zone resulting from a series of projected withdrawal rates from that zone of the aquifer (estimated by the U.S. Army Corps of Engineers, written commun., 1978) using a simplified conceptual model of the aquifer system.

Previous Investigations

The Geological Survey has been collecting water resources data in Jacksonville, Duval County, for several decades. Data are available from field measurements (including aquifer tests), hydrologic laboratory analyses, and an ongoing investigation of the Floridan aquifer.

The geohydrology of northeast Florida has been described by Cooper and others (1953), Chen (1965), Leve (1968), and Snell and Anderson (1970). Countywide surveys of ground water in Duval and neighboring counties have been conducted by Bermes and others (1963), Leve (1966), Leve and Goolsby (1969), Bentley (1977b), and Fairchild (1977).

More detailed investigations of the Floridan aquifer in northeast Florida have been conducted by Bentley (1977a), Fairchild and Bentley (1977), Miller and others (1978), Leve (1978), and Phelps (1978).

HYDROLOGIC SETTING

General Geohydrology

The Floridan aquifer consists primarily of a thick sequence of highly permeable Eocene limestone and dolomite beds. The Oligocene Suwannee Limestone, which is a part of the aquifer in most of northeast Florida, is absent in most of Duval County. Semipermeable deposits of Miocene to Holocene age overlie the aquifer and confine the water in the aquifer under artesian pressure. The Ocala and Lake City Limestones are the principal sources of freshwater, while the dense dolomitic beds of the Avon Park Limestone generally produce little water. About 500 feet of the lower part of the Lake City and upper part of the Oldsmar Limestones is less permeable than other zones of the aquifer, and acts as a semiconfining unit below the major pumping zone of the aquifer. The lower part of the Oldsmar Limestone (henceforth referred to as the lower permeable zone) is highly permeable but it is not developed as a source of water supply. A generalized summary of the geologic units and their waterbearing properties is given in table 1.

Upper Confining Unit

The upper confining unit, which overlies the Floridan aquifer in Duval County, is the Hawthorn Formation of Miocene age. It consists of sand, shell, and limestone deposits of low to moderate permeability, separated by thin, nearly impermeable clay beds. The clay beds confine the water in underlying permeable zones.

The hydraulic parameters of the upper confining bed are summarized in table 2. Because the thickness, as determined from geologic well logs, does not vary greatly from one area of the county to another, a uniform thickness of 400 feet is assumed. Vertical hydraulic conductivity is estimated based on laboratory analyses of cores from test wells in Duval County (written commun., U.S. Geological Survey Hydrologic Laboratory, 1976), and a similar value reported by Miller and others (1978, p. 95) in the nearby Osceola National Forest area. The value of specific storage is an estimate, partially based on laboratory analyses of core samples and field extensometer tests of the Hawthorn Formation (Miller and others, 1978, p. 95). Local variations in the stratigraphy and the lack of detailed studies of the hydraulic properties of the Hawthorn, do not permit a more detailed areal differentiation of the hydraulic parameters.

Floridan Aquifer

The Floridan aquifer is approximately 1,600 feet thick in Duval County. The upper 1,000 feet consists of alternating layers of soft, highly permeable limestone and hard crystalline limestone and dolomite, and is the principal source of freshwater. Most wells are cased to about

Table 1.—Generalized geologic units in Duval County and their hydrologic properties.

Geologic age	Stratigraphy		Approximate thickness (ft)	Lithology	Hydrogeologic unit		Hydrologic properties
Holocene to Pliocene	Surficial deposits		100	Discontinuous sand, clay, and shell beds	Surficial aquifer		Sand and shell deposits provide local limited water supplies.
Miocene	Hawthorn Formation		400	Interbedded phosphatic sand, clay, marl, and limestone	Upper confining unit		Sand, shell, and limestone deposits provide local limited water supplies, both artesian and non-artesian. Low permeability clays serve as the principal confining beds for the Floridan aquifer below.
Eocene	Ocala Limestone		500	Massive fossiliferous chalky to granular marine limestone sequence	Floridan Aquifer	Upper permeable zone (pumping zone)	Principal source of ground water in Duval County. High permeability overall.
	Avon Park Limestone			Alternating beds of massive granular and chalky limestones, and dense dolomites			Water bearing layers separated by low permeability limestone and dolomite.
	Lake City Limestone		500				
	Oldsmar Limestone	Upper unit	450			Semiconfining zone	Low permeability limestone and dolomite
		Lower unit	150			Lower permeable zone	Highly permeable. Increases in salinity noted.
Paleocene	Cedar Keys Limestone		?	Uppermost appearance of evaporites; dense limestones	Lower confining unit		Highly mineralized water, very low permeability.

Table 2.--Estimated hydraulic parameters of the hydrologic units in Duval County.

Units	Average thickness (ft)	Specific storage (per ft)	Vertical hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Leakance (per day)
Upper confining unit	400	$1.0x10^{-5}$	$1.0x10^{-3}$		$2.5x10^{-6}$
Floridan aquifer production zone	1,000	$1.0x10^{-6}$		$8.0x10^{4}$	
semiconfining zone	500	$1.0x10^{-6}$	$2.0x10^{-2}$		$4.0x10^{-5}$

20 feet below the top of the aquifer and penetrate less than 700 feet into the aquifer, although a few penetrate the entire productive zone.

Test drilling indicates (Leve and Goolsby, 1967) that about 500 feet of the lower part of the aquifer (the lower part of the Lake City and upper part of the Oldsmar Limestones) consists of limestone and dolomite which have a low permeability (semiconfining zone, table 1). Beneath the semiconfining zone, about 150 feet of the lower part of the Oldsmar is highly permeable. Permeability decreases below the Oldsmar, and the water becomes highly mineralized. The uppermost stratigraphic occurrence of persistent evaporite deposits in the Cedar Keys Limestone is generally recognized as the base of the Floridan aquifer.

Aquifer parameters were estimated by applying the Hantush method to the data from more than 20 aquifer tests made in Duval County since 1940. Many of these test results were reported by Leve (1966). The locations of selected tests of the upper permeable zone (pumping zone), as well as the thickness of aquifer penetrated in each test and the calculated transmissivities, are shown in figure 1. Calculated values of transmissivity range from 2.0×10^4 to 2.0×10^5 ft^2/d (fig. 1). Variations in calculated transmissivity values probably are due to complex field conditions, such as layering in the aquifer, solution features, and possible fractures (Leve, 1978). The local relationship between calculated transmissivity and thickness of penetration has been demonstrated by Bentley (1977a, p. 41). Based on considerations of anisotropy, well penetration, and details of the individual pumping tests, an average transmissivity for the upper permeable zone (pumping zone) in Duval County is estimated to be 8.0×10^4 ft^2/d.

A representative value of specific storage, 1×10^{-6} per ft, based on the test data, agrees with Lohman's (1972, p. 8) value for artesian aquifers. The specific storage of the aquifer is believed uniform over the area of investigation.

The low permeability zone in the lower part of the Lake City and upper part of the Oldsmar Limestones acts as a semiconfining unit, although the zone is recognized as part of the Floridan aquifer. Few hydrologic data are available for this zone. Pride and others (1966, p. 68) reported that in the Green Swamp area in central peninsula Florida, the coefficients of vertical permeability of the lower part of the Lake City and upper part of the Oldsmar Limestones are 0.003 and 0.02 gal/d/ft (4.0×10^{-4} ft/d and 2.7×10^{-3} ft/d respectively).

Based on estimates of relative differences in vertical hydraulic conductivity between the overlying confining unit, the upper permeable zone and the lower confining unit, these values are considered to be too low for Duval County. A vertical hydraulic conductivity of 2.0×10^{-2} ft/d is used in this study. Since field data were unavailable, this value is based primarily on the vertical hydraulic conductivity determined during ongoing investigations.

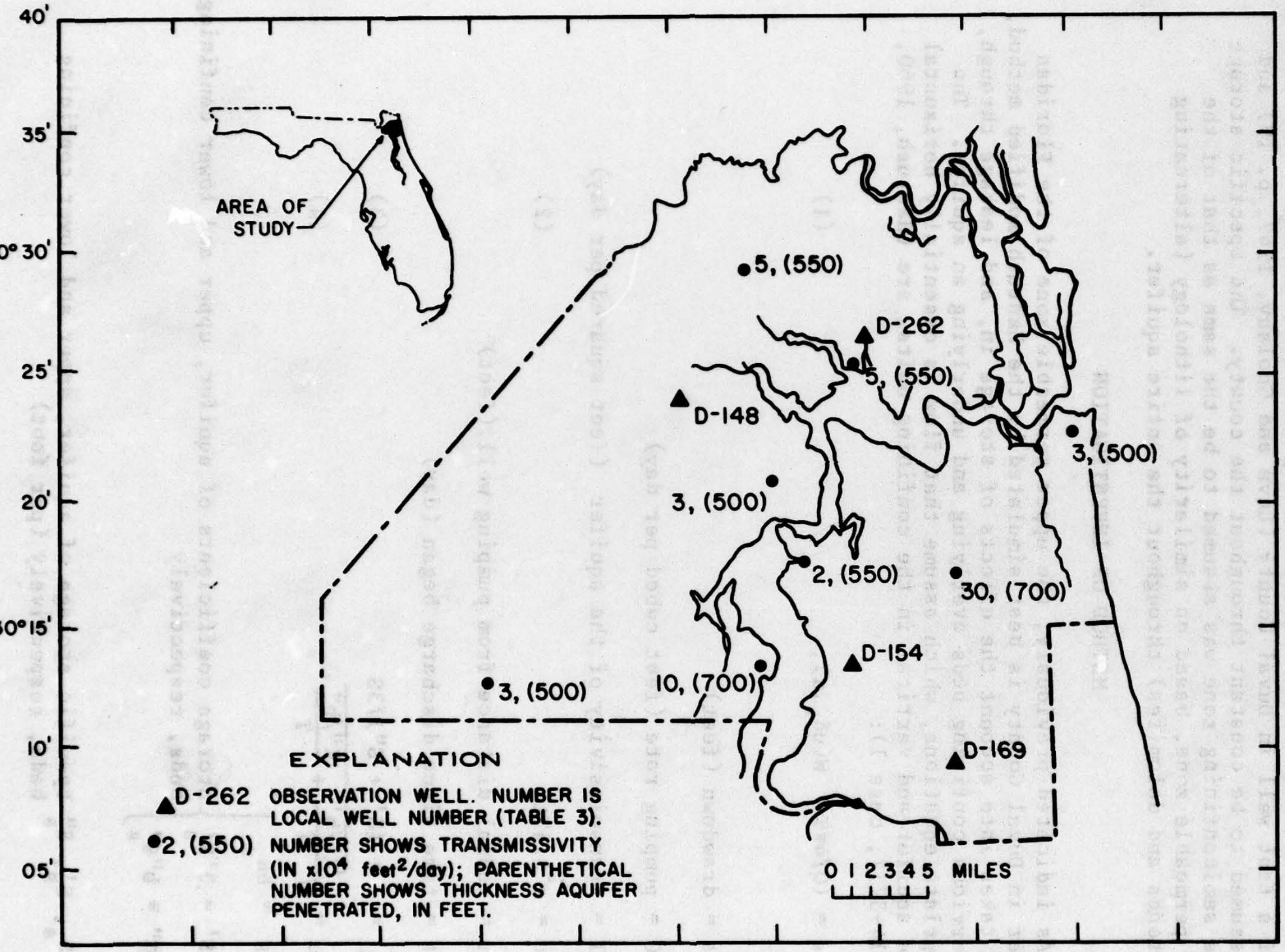

Figure 1.--Measured transmissivity values in Duval County, and locations of selected observation wells.

Thickness of the lower semiconfining zone was determined from the log of a test well in Duval County (Leve and Goolsby, 1967, p. 19) and was assumed to be constant throughout the county. The specific storage of the semiconfining zone was assumed to be the same as that of the upper permeable zone, based on similarity of lithology (alternating limestones and dolomites) throughout the entire aquifer.

METHOD OF INVESTIGATION

As indicated previously, the upper permeable zone of the Floridan aquifer in Duval County is best simulated by the Hantush modified method, which takes into account the effects of storage in, and leakage through, semipervious confining beds overlying and underlying an aquifer. The appropriate equations, which assume that flow is essentially horizontal in the aquifer and vertical in the confining units, are (Hantush, 1960, p. 3714-3717, case 1):

$$s = (Q/4\pi T) \quad W(u\delta_1, \alpha), \tag{1}$$

where

s = drawdown (feet)

Q = pumping rate (feet cubed per day)

T = transmissivity of the aquifer (feet squared per day)

$$u = r^2 S/4Tt \tag{2}$$

r = radial distance from pumping well (feet)

t = time since discharge began (day)

$$\delta_1 = 1 + (S' + S'')/3S \tag{3}$$

$$\alpha = r\sqrt{\frac{K'/b'}{T} + \frac{K''/b''}{T}} \tag{4}$$

$$\left.\begin{aligned} S &= bS_s \\ S' &= b'S'_s \\ S'' &= b''S''_s \end{aligned}\right\}$$ Storage coefficients of aquifer, upper and lower confining beds, respectively

S_s, S'_s, S''_s Specific storage of aquifer, upper and lower confining beds, respectively (per foot)

b, b', b'' Thickness of aquifer, upper and lower confining beds, respectively (foot)

K = Lateral hydraulic conductivity of aquifer (feet per day)

K', K" Vertical hydraulic conductivity of upper and lower confining beds, respectively (feet per day)

and $W(u\delta_1, \alpha)$ is equivalent to the well function for leaky aquifers tabulated by Hantush (1956): $W(u,r/B) = \int_u^{\infty} (1/y) \exp(-y-r^2/4B^2y)dy,$ (5)

where $B = \sqrt{Tb'/K'}$ and all other terms are as defined above. Equation (5) is a special case of equation (1), in particular the limit as S', S", and K" approach zero.

Equation (1) yields exact values of drawdown for pumping times greater than the larger of the two values 5b"S"/K" and 5b'S'/K', which in this study are 90 days and 8,000 days (22 years), respectively. To obtain exact values of drawdown for times less than 22 years it would be necessary to compute families of time-drawdown curves for each set of aquifer parameters for each pumping rate for each radius based on Hantush's (1960, p. 3716) short-time and long-time formulas, and interpolate between the curves. Errors based on these interpolations are small (less than 5 percent) for the time intervals of interest in the study (greater than 5 years). An example of such a family of time-drawdown curves is shown in figure 2.

The above criteria for determining drawdowns, it should be observed, are based on mathematical approximations to the exact solution of the drawdown equation, which is complex and difficult to evaluate numerically. The criteria are not a function of the hydrologic properties alone. Neuman and Witherspoon (1969, p. 818-821), in an analyses of Hantush's equations, demonstrated that his time criteria are quite conservative. Further, if the chosen hydraulic parameters are valid, more than 95 percent of the leakage into the upper permeable zone of the Floridan aquifer in Duval County comes upward through the underlying semiconfining zone. Recognizing the importance of upward leakage, therefore, the Hantush equation as stated is assumed to be appropriate for periods longer than 5 years.

Because the physical boundaries of the Floridan aquifer lie much further from the area of investigation than the maximum radius of influence for the pumping rates tested, the effects of boundary interference were assumed to be negligible.

Calculation of Drawdown

The following simplifying assumptions were made in calculating drawdowns:

(1) Discharge was from a single pumping well, for each pumping center.
(2) Calculated drawdowns were assumed to be independent of all other factors such as initial potentiometric surface or overlapping pumping effects between adjacent areas.

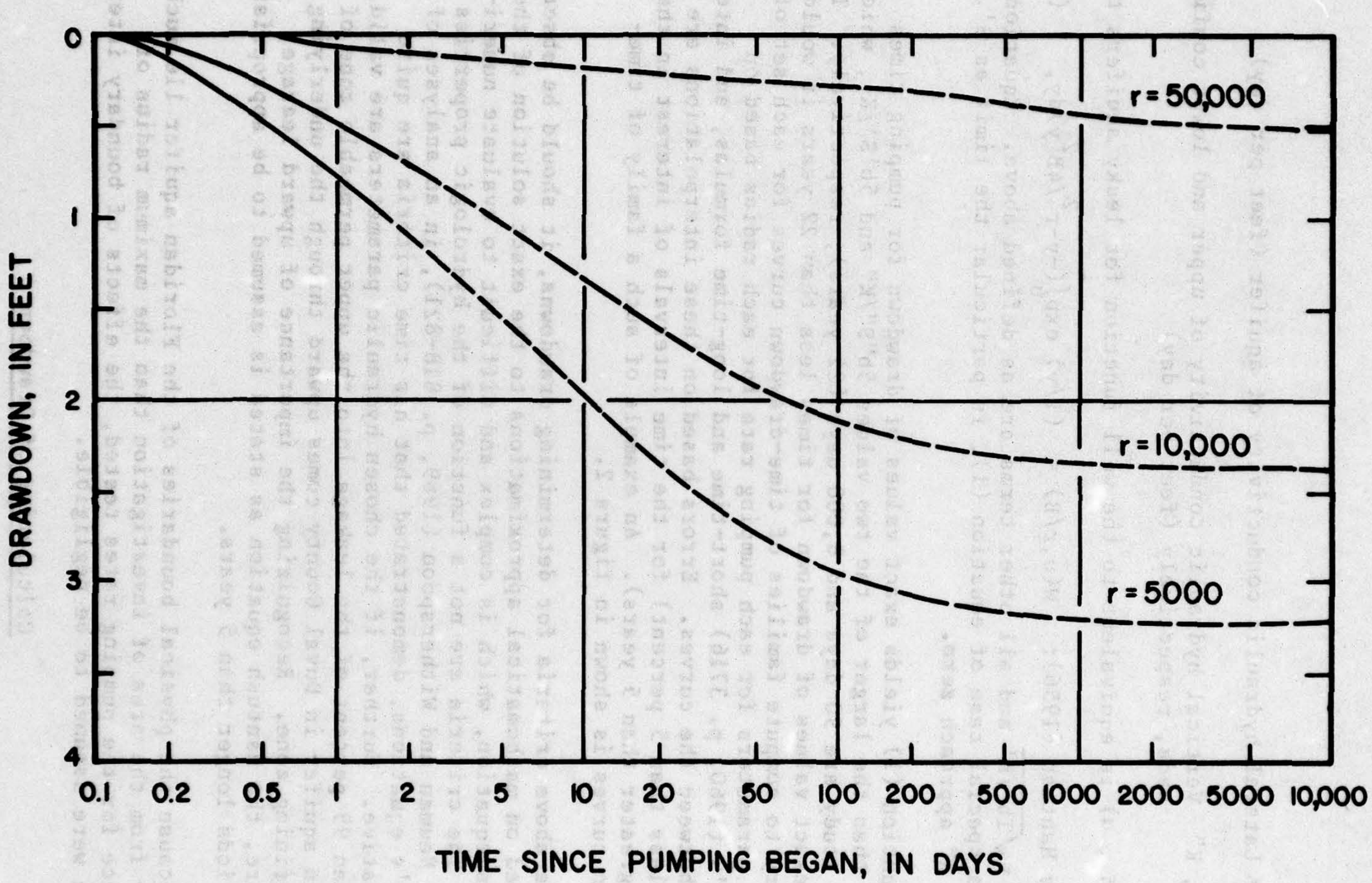

Figure 2.--Drawdown versus time curves for selected aquifer characteristics. Pumping rate, Q equals 5 million gallons per day.

(3) Heads were assumed constant in both the overlying surficial aquifer and the lower permeable zone.

Although the calculated drawdowns near the pumping centers generally are overestimated, they provide a reasonable indication of potential problem areas. A sample drawdown calculation is shown below:

Let r = 10,000 ft, t = 8000 d, Q = 5 Mgal/d and computing the aquifer parameters from table 2:

$$\delta_1 = 1 + \frac{(S' + S'')}{3S} = 1 + \frac{(4\text{x}10^{-3} + 5\text{x}10^{-4})}{3\ (1\text{x}10^{-3})} = 2.5$$

$$u = \frac{r^2 S}{4Tt} = \frac{(1\text{x}10^4\ \text{ft})^2\ (1\text{x}10^{-3})}{4(8.0\text{x}10^4\ \text{ft}^2/\text{d})\ (8000\ \text{d})} = 3.9\text{x}10^{-5}$$

and $u\delta_1 = 9.8\text{x}10^{-5}$

$$\alpha = r\sqrt{\frac{K'/b'}{T} + \frac{K''b''}{T}} = (1\text{x}10^4\ \text{ft})\sqrt{\frac{(2.5\text{x}10^{-6}/\text{d} + 4.0\text{x}10^{-5}/\text{d})}{8.0\text{x}10^4\ \text{ft}^2/\text{d}}} = 0.2$$

Then $W(u\delta_1, \alpha) = 3.4$ (Hantush, 1956, table 2)

$$s = \frac{Q}{4\pi T} W(u\delta_1, \alpha) = \frac{(5\text{x}10^6\ \text{gal/d})(0.134\ \text{ft}^3/\text{gal})(3.4)}{4\pi(8.0\text{x}10^4\ \text{ft}^2/\text{d})} = 2.3\ \text{ft}$$

Drawdown-versus-distance graphs were calculated for pumping rates of 3, 5, 20, and 50 Mgal/d (figs. 3-6). Three to five Mgal/d are typical pumping rates for municipal wells in Jacksonville. Therefore, for the higher pumping rates, calculated drawdowns close to the assumed single pumping well are somewhat greater than would actually result from a well field producing 20 or 50 Mgal/d, assuming that the well field were designed to minimize drawdown. Drawdowns are calculated using three values of transmissivity to reflect the variability observed from the aquifer tests; a low value of $2.0\text{x}10^4\ \text{ft}^2/\text{d}$, the average value of $8.0\text{x}10^4\ \text{ft}^2/\text{d}$, and a high value of $2.0\text{x}10^5\ \text{ft}^2/\text{d}$.

Time intervals for pumping at the various rates ranged from 5 to 50 years. Maximum drawdown for each pumping rate is effectively reached and maintained within 5 years, independent of the pumping rate. Thus, one set of steady-state distance-drawdown curves for each pumping rate suffices for studying the effects of long-term withdrawals.

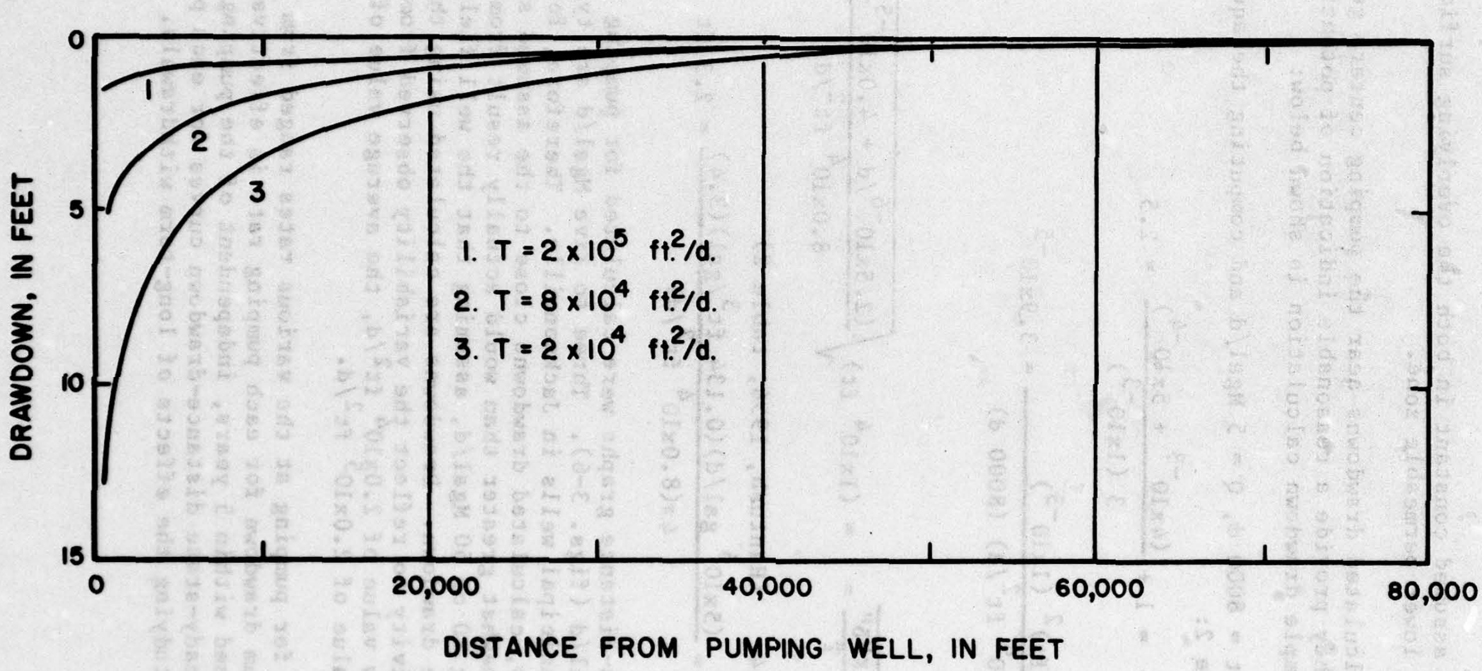

Figure 3.--Steady-state distance-drawdown curves for upper permeable zone for selected aquifer characteristics. Pumping rate, Q equals 3 million gallons per day.

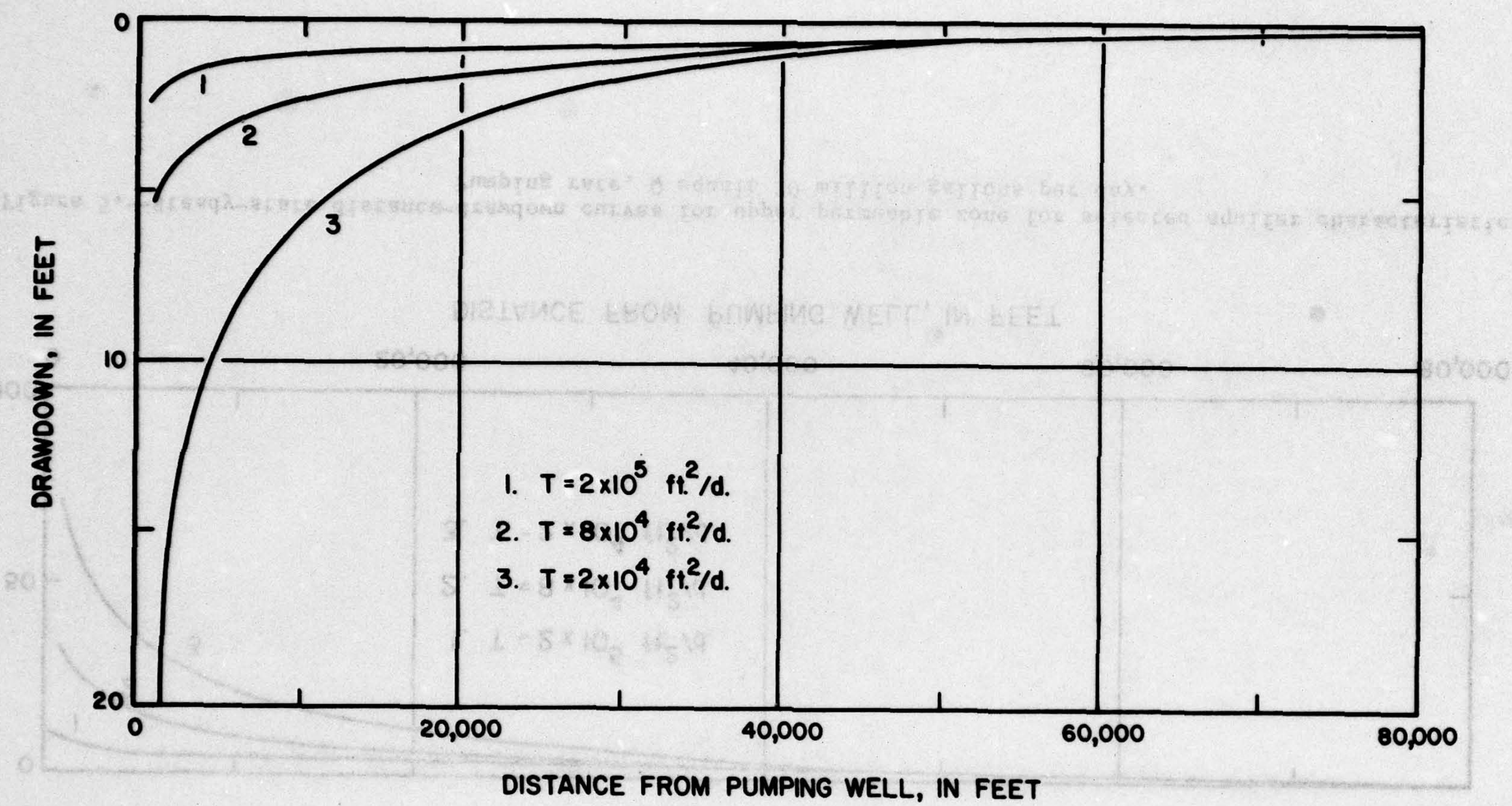

Figure 4.--Steady-state distance-drawdown curves for upper permeable zone for selected aquifer characteristics. Pumping rate, Q equals 5 million gallons per day.

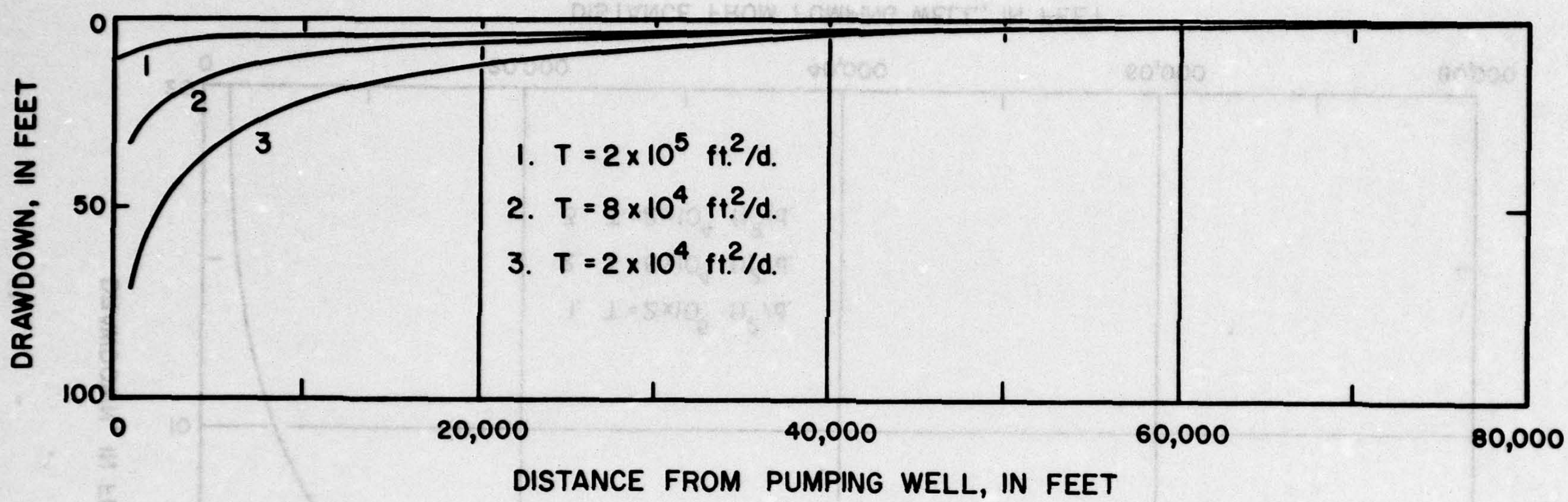

Figure 5.--Steady-state distance-drawdown curves for upper permeable zone for selected aquifer characteristics. Pumping rate, Q equals 20 million gallons per day.

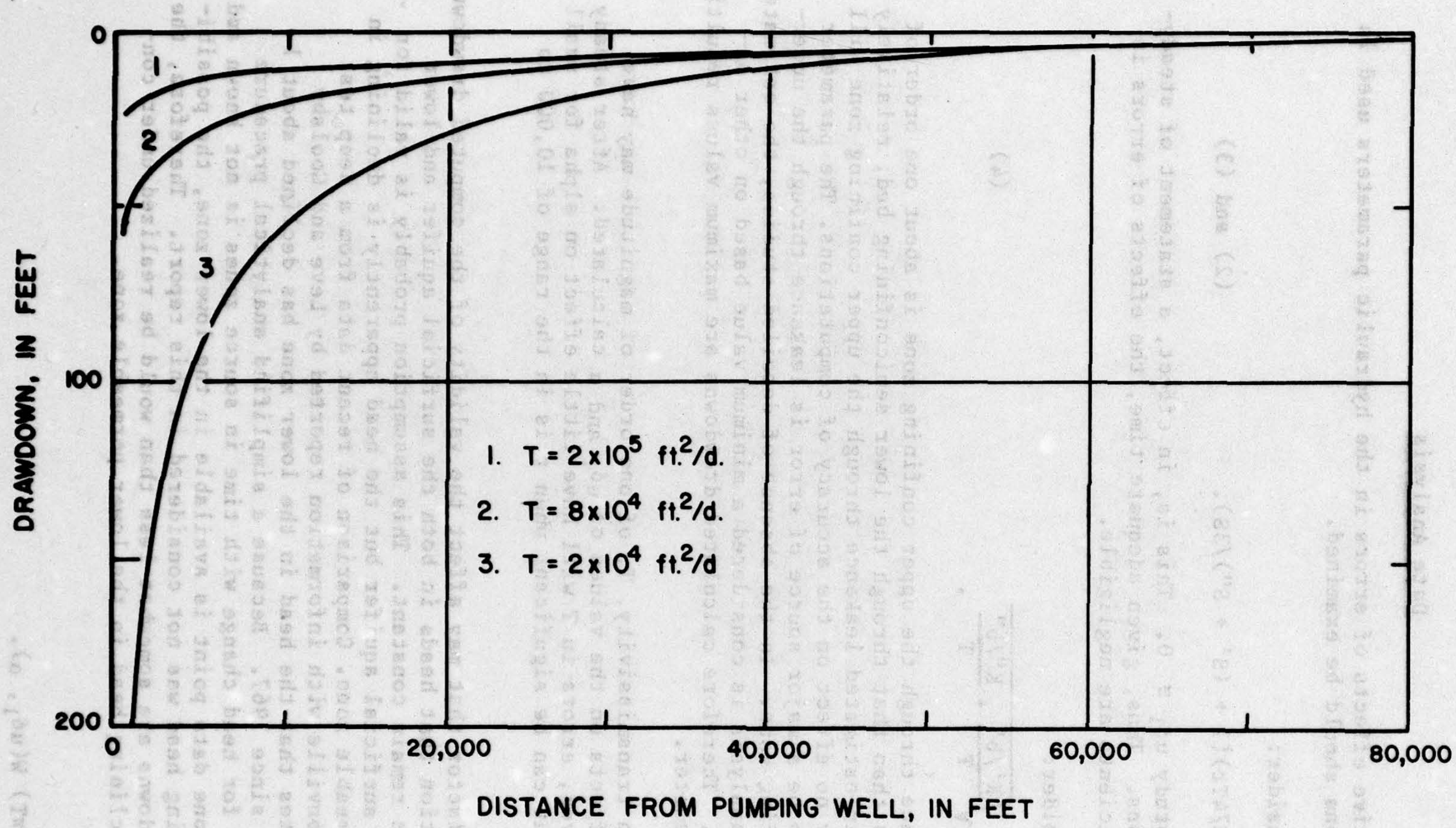

Figure 6.--Steady-state distance-drawdown curves for upper permeable zone for selected aquifer characteristics. Pumping rate, Q equals 50 million gallons per day.

Data Analysis

The relative effects of errors in the hydraulic parameters used in the calculations should be examined.

First consider:

$$u\delta_1 = (r^2S/4Tt)(1 + (S' + S'')/3S). \qquad (2) \text{ and } (3)$$

In this study $u\delta_1 \cong 0$. This is, in effect, a statement of steady-state conditions. Thus, given adequate time, the effects of errors in storage coefficients are negligible.

Next consider:

$$\alpha = r\sqrt{\frac{K'/b'}{T} + \frac{K''/b''}{T}}\,. \qquad (4)$$

Because leakance through the upper confining zone is about one order of magnitude less than that through the lower semiconfining bed, relatively large errors in estimated leakance through the upper confining zone will have virtually no effect on the accuracy of computations. The parameter most likely to be a major source of error is leakance through the underlying semiconfing zone. In the absence of detailed studies, the estimate used in this analysis is considered a minimum value based on other on-going studies. Therefore calculated drawdowns are maximum values resulting from this parameter.

Errors in transmissivity, T, of one order of magnitude may have significant effects on the values of $u\delta_1$ and α calculated. After steady flow is achieved, errors in T will have little effect on alpha for small values of r but can be signficant when r is in the range of 10,000 to 50,000 feet.

A final factor that may affect the validity of the computed drawdowns is the assumption that heads in both the surficial aquifer and lower permeable zone remain constant. This assumption probably is valid for the overlying surficial aquifer but the head apparently is declining in the lower permeable zone. Comparison of recent data from a deep test well in Jacksonville with information reported by Leve and Goolsby (1967) indicates that the head in the lower zone has declined about 1 foot per year since 1967. Because a simplified analytical procedure that accounts for head change with time in source zones is not known and because only one data point is available in the lower zone, the possibility of changing head was not considered in this report. Therefore, the computed drawdowns are somewhat less than would be realized under conditions of declining head in the lower permeable zone.

Finally:

$$s = (Q/4\pi T)\, W(u\delta_1, \alpha).$$

Errors in the value of the well function, $W(u\delta_1, \alpha)$, were evaluated above. Variations in both the pumping rate and the transmissivity can have significant effects on the calculated drawdowns. A comparison of distance-drawdown figures 3-6 indicates the magnitudes of these effects.

Data Verification

The estimated aquifer parameters were verified by comparing calculated drawdowns with historical water level declines in selected wells. Four wells tapping the Floridan aquifer (table 3) were selected and the change in measured water level in each well over the 15 year period 1960-75 was calculated. Centers of pumping in Duval County were identified from city records, and average pumping rates were calculated. Distances between pumping centers and each of the four observation wells were determined. The drawdown at each observation well site is the sum of the drawdowns caused by each pumping center. A uniform T value of 8×10^4 ft^2/d was used in calculating the drawdowns. Drawdowns were calculated both by the Hantush (1960) modified leakance formula and the Theis (1935) non-leaky equation for confined aquifers.

Several factors could account for the differences in calculated and observed drawdowns (table 3). First, historical water use data for Duval County are sparse (Leve, 1966; Pride, 1970; Leach, 1978). Based on available data, an average total ground-water withdrawal for the period 1960-75 was estimated to be 125 Mgal/d, but errors in drawdown are directly related to errors in pumpage estimates.

Another factor is that possible long-term regional trends in water levels were not considered. Effects of climatic fluctuations, if present, are not easily recognizable, overprinted by the larger effects of drawdown caused by pumping.

The calculated drawdowns for wells D-148 and D-262 significantly overestimate measured drawdowns. D-148 is less than 2 miles from a city well field which pumps about 3 Mgal/d, and D-262 is approximately 4,000 feet from an industrial well field pumping about 20 Mgal/d. The effects of possible errors in transmissivity and leakance (and thus also in $u\delta_1$, and α) are greater at observation wells close to pumping wells, particularly when pumping rates are high.

As a check on the applicability of the Hantush modified method, and to provide an upper limit for drawdown, the Theis equation for nonleaky confined aquifers also was used to calculate drawdowns. As data in table 3 indicate, the failure to consider leakance greatly increases calculated drawdowns. The Hantush modified method, which includes the effects of leakage from the confining beds, is therefore considered a much more realistic approximation to the aquifer system than the Theis equation for nonleaky confined aquifers.

Table 3.--Observed and calculated water levels in selected observation wells in Duval County.

Local well number	USGS site identification number[1]	Depth (ft)	Water level (ft above MSL) 1960	Water level (ft above MSL) 1975	Water level change (ft) Measured	Water level change (ft) Calculated[2] (Hantush)	Water level change (ft) Calculated[3] (Theis)
D-154	301324081352601	625	42.4	34.7	-7.7	-8.6	90
D-148	302410081443501	625	44.3	36.8	-7.5	-12.4	100
D-169	300824081305401	700(?)	44.5	40.0	-4.5	-3.8	80
D-262	302608081350901	1,400	44.8	37.3	-7.5	-21.5	80

1 Site identification number: Approximate latitude and longitude of well. For example, 301324081352601 can be read as 30°13'24" N latitude, 081°35'26" W longitude, well 01 at that location. Well locations are shown in figure 1.

2 Based on equation 1 (p.), with $T = 8.0 \times 10^4$ ft^2/d.

3 Based on Theis' equation for non-leaky confined aquifers, $s = (q/4 T) W(u)$, with $T = 8.0 \times 10^4$ ft^2/d and t = 15 years.

Given the above considerations, the calculated drawdowns are considered reasonable estimates of observed water level changes in Duval County. Therefore aquifer parameters estimated for this study are considered representative and can be used to evaluate aquifer response to future pumping rates.

DISCUSSION

Hydrologic properties of the upper permeable zone of the Floridan aquifer and overlying and underlying beds were estimated from available aquifer test data, geologic logs of wells, and other ongoing investigations of the aquifer system. The Hantush modified method, which takes into account leakage from all confining units, was used to calculate transmissivities and storage coefficients. The accuracy of the parameter estimates was checked by comparing calculated drawdowns in selected observation wells to measured water level declines. Distance-drawdown curves were then calculated based on hypothetical withdrawal rates for extended periods of time.

In order to simplify the calculations, several assumptions were made. For parameter calibration, only the major pumping centers (greater than 3 Mgal/d) were considered in the calculations. These centers *account for* 70 Mgal/d, although total pumpage in Duval County in 1975 was about 150 Mgal/d. Only the major pumping centers have greatly increased their pumpage in the time period of interest; the effects of small users are believed to have remained relatively constant over this interval.

The distance-drawdown curves for projected pumping rates were calculated assuming that a single well was pumping at various rates from 3 to 50 Mgal/d. Simultaneous pumping elsewhere in the county was not considered. Total drawdown at any particular point should be calculated by summing the individual effects of each pumping center.

In actual practice economic constraints generally limit production from a single well to about 3-5 Mgal/d. Drawdowns at distances of less than about 2 miles from the center of pumping would be less for a group of pumping wells than for a single pumping well of comparable pumpage. For example, with a single well pumping 50 Mgal/d, the calculated drawdown at an observation well 5,000 feet away is about 40 feet. A linear arrangement of 10 wells, 1,000 feet apart, each pumping at 5 Mgal/d would achieve the same production rate while drawdown at a point 5,000 feet away from the center of the well field and perpendicular to it would be about 30 feet. Other well field designs might further reduce drawdown. Effects of different pumping rates are likewise most noticeable close to the pumping centers.

Figures 3-6 also show the significance of variations in transmissivity on calculated drawdowns: $u\delta_1$, and α, as mentioned previously, both depend on T; T is even more significant in the final calculation $s = (Q/4\pi T)\, W(u\delta_1, \alpha)$.

Variations in transmissivity are a possible cause of the anomalously large calculated drawdowns at well D-262. The major (20 Mgal/d) pumping center about 4,000 feet away from D-262 accounts for nearly 80 percent of the calculated drawdown and, as previously noted, the potential for error due to variation in transmissivity is greatest for small radii. Another factor in the large calculated drawdowns at well D-262 is that well D-262 penetrates about 900 feet of the pumped zone, while the other observation wells penetrate only about the upper 100-200 feet of the aquifer. Vertical anisotropy could cause drawdown in the lower zone to be less than that in the upper zone, thus, creating intraborehole flow in the observation well. The effect would be that the measured (vertically integrated average) drawdown is less than that in only the upper zone (represented by the calculated value). These factors also suggest that the average value of transmissivity estimated in this study may be lower than the true value for the fully penetrated aquifer.

Further reduction in aquifer water levels as a result of increased pumpage may result in a deterioration of water quality. Increases in salinity of the lower permeable zone of the Floridan aquifer have been noted at Fernandina Beach (Fairchild and Bentley, 1977) in response to withdrawals from the upper part of the aquifer. Chloride concentration of water from the lower permeable zone in test well (local number D-425) in Duval County was about 30 mg/L when the well was drilled (Leve and Goolsby, 1967, table 1). By 1974 the concentration had increased to about 200 mg/L and has remained relatively constant since then. Most wells penetrating the upper permeable zone of the Floridan aquifer in eastern Duval County have maintained a constant chloride concentration of about 20 mg/L, but from 1972 to 1978, the concentration in at least one city production well (Lovegrove pumping station) has increased to about 100 mg/L. Similarly, chloride concentrations in a well at Fort George Island have increased gradually since data collection began in 1940 from about 60 mg/L to a present value of about 170 mg/L. The increase in chloride concentrations in both wells is attributed to upward movement of water from deeper sources.

Increased withdrawals from the upper part of the Floridan aquifer would be accompanied by further declines in head in the lower zone. These declines would facilitate further intrusion of saltwater into the upper zones of the aquifer either from lateral sources or from deeper sources. In most areas, highly saline water from the lower confining unit (Cedar Keys Limestone) should be inhibited from upconing by the unit's generally low hydraulic conductivity. However, locally, subsurface solution features and faults may provide routes for upward movement of saltwater. A thorough evaluation of potential increases in salinity is beyond the scope of this study.

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